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Angular dependent reflectance spectroscopy of RGBW pigments

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Short abstract

Traditional printing relies primarily on subtractive color mixing techniques. In this case, optical color mixing is achieved by one of the established halftoning methods that use Cyan, Magenta, Yellow and Black (CMYK) primaries on a reflective white substrate. The reason behind the subtractive color mixing in printing is the high absorbance of available pigments used in inks. A new type of mica-based pigments that exhibit high reflectivity at Red, Green, Blue and White (RGBW) spectral bands was recently introduced by Merck (Spectraval™). Printing with RGBW primaries on black background allows additive color mixing in prints. While offering excellent color depth, the reflected spectra of such pigments vary with the angles of incidence and observation. As a result, new approaches in modelling the appearance of prints as well as strategies for color separation and halftoning are needed. The prior optical characterization of the reflective inks is an essential first step. For this purpose, we have used Spectraval™ pigments to prepare acrylic based inks, which we applied on glass slides by screen printing. In this work, we measured the relative spectral bidirectional reflection distribution of Red, Green, Blue and White reflective inks. The measurements were conducted on an experimental set up consisting of a goniometer, spectrometer, and a xenon light source. Based on the measurements, we simulate the reflectance spectra under diffuse illumination and demonstrate ratios of red, green, and blue spectral components for different observation angles of individual inks and their combinations.

Keywords: RGB printing, BRDF, spectroscopy, special effect inks

1. Introduction and background

Mica minerals are widely used in the production of coloring media in a range of applications, including printing and cosmetics. The preparation process of mica-based pigments is a complicated process that depends on the desired properties. After grounding the mineral into powder, the process can include dyeing the mica particles, coating them with metallic oxide or optimizing the particles' surface structure, depending on the desired properties (Maisch, Stahlecker and Kieser, 1996). The resulting inks and coatings based on treated mica flakes can provide visual effects such as goniochromatism, or pearlescent (metallic) effects. The recently introduced Merck Spectraval™ pigments are optimized for selective light reflectivity at the RGBW bands (Merck, 2021). This property allows additive color mixing in printing, which is not possible with traditional inks according to the subtractive model. It is possible to use Spectraval™ pigments in commercial printing such as screen printing or lithography (Klein, Parraman and Voges, 2019; Parraman and Klein, 2021) however the methods have to be adapted to the size of the pigments (1–25 μm) i.e. using lower print resolution. The appearance of the prints, however, is difficult to predict, due to the optical properties of highly reflective pigments applied on their own or in combination with absorbing pigments (Trujillo-Vazquez, et.al., 2022).

In conventional color printing, the colorants (inks) are characterized by their spectral power distribution, in combination with the reflective substrate. Various color prediction models and halftoning techniques have been implemented to achieve accurate color reproduction, using subtractive color mixing of dye-based inks. As the main input, such models require the spectral reflectivity of the primary inks, as well as overlapping inks (the so called Neugebauer primaries). The spectral reflectance is assumed to be constant for all viewing and illumination directions, a property called Lambertian reflectance. For an accurate color reproduction, effects such as mechanical and optical dot gain need to be compensated for in the color separation and halftoning process.

In the case of reflective inks like Spectraval, the assumption of Lambertian surface reflectance does not hold. Furthermore, the reflective RGBW inks used in our experiment can exhibit goniochromatic properties. The main property of the inks studied here, is that the nominal pigment color (red, green, or blue) can be observed only for a specific combination of angles of illumination and observation (or specific angle of observation in case of diffuse illumination). For non-optimal observation angles, the perceived color of the inks fades towards grayish or white. The light-matter interaction leading to the color formation of these inks is therefore different from the well-characterized conventional CMYK inks. Rather than selective absorption, and high scattering at specific wavelengths, selective light interference on the pigment coating may provide an explanation for the observed visual effects (Du, et al., 2008). Thus, full optical characterization is required for accurate appearance modeling of prints made with RGBW primaries. This characterization includes but is not limited to the angularly dependent relative reflected spectral composition (Tomić, et al., 2017). Additionally, for further developments of colorant mixing and halftoning methods, the modelling of optical dot gain needs to be refined to describe the optical properties of the RGB inks more accurately (Meruga, 2014).

In our work, we measure angularly dependent reflected spectra of inks prepared with available pigments with nominal red, green, blue, and white colors. As one of possible demonstrations of the obtained results, we present calculated relative spectra for diffuse illumination. Additionally, we compare color saturation of inks prepared with low and high concentration of pigments and simulate spectra of their mixtures in case of optical mixing.

2. Materials and methods

Samples for our study were prepared by mixing (Merck Spectraval™) pigments with acrylic binder. For our experiment we prepared inks with 10 wt% (low) and 30 wt% (high) concentration of pigments. The inks were applied on glass slides by screen printing. Samples with 1 layer and 4 layers were prepared for both concentrations. Figure 1 demonstrates how the inks are perceived visually under diffuse daylight at various angles of observation. For demonstration purposes, inks prepared with a high concentration of pigments were applied on black paper and wrapped around a cylinder.

Figure 1: Photographs of inks prepared with nominal Red (left), Green (middle) and Blue (right) pigments, inks were applied on black paper and wrapped around a cylinder under diffuse daylight illumination

Visible color variations were characterized by recording spectral reflectance distributions for a set of combinations of angles of incidence and observation (reflected angles). If absolute values of reflected radiance are known, the color of the samples can be represented in one of the CIE color spaces. We observe wavelength dependent reflectance of the samples to obtain the spectral BRDF in arbitrary units (scaled to the unknown value of solid angle):

$$R(\omega_i, \omega_o, \lambda) = \frac{dL'_o(\omega_i, \omega_o, \lambda)}{L'_i(\omega_i, \lambda) \cdot \cos\theta_i d\omega_i}, \qquad [1]$$

where measured quantities L'_o and L'_i are spectrometer responses proportional to the reflected and illuminated radiances, ω_i (ω_o) are the directions of incidence (observation) and θ_i is the angle between the direction of incidence and sample normal. Measurements were made in the plane of incidence.

Our experimental set up for the spectral BRDF measurements consists of a goniometer, a xenon lamp with focusing lens and a spectrometer. Figure 2 depicts the experiment and the notation of angles of incidence, observation, and specular direction of reflectance. We set illumination angles to 15°, 20°, 30°, 40°, 50°, 60°, and 70°. Due to the limitations of the experimental measurement set up, only certain combinations of incidence and reflectance angles were feasible to measure. Reflected spectra were collected for a discrete set of observation directions with dense (1–2° step) scanning around specular reflectance direction and 5–10° step with further inclination from the direction of the specular reflection, for each angle of incidence. During the analysis of the measured results, we calculated relative reflectance of the inks by subtracting the background noise and dividing measured spectra of the samples by the measured spectral response of the light source. The measured relative spectra were scaled to the maximum value of 1. After collecting and analyzing spectral BRDF data, we simulate angular spectral reflectance distributions under diffuse illumination by calculating cosine weighted average of normalized measured reflected spectra for different observation angles, as:

$$R(\omega_o, \lambda) = \frac{\sum_{\omega_i} R(\omega_i, \omega_o, \lambda) \cdot \cos(\theta_i)}{\sum_{\omega_i} \cos(\theta_i)} \qquad [2]$$

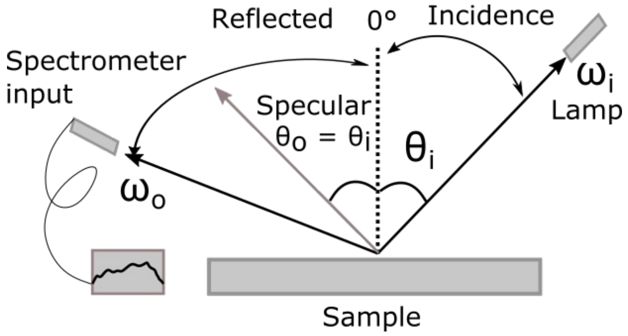

Figure 2: Experimental set up and angle notation for spectral BRDF measurements with demonstrated definition of specular reflectance direction

The perceived color saturation at different observation angles can be characterized by the relative ratio of corresponding spectral components (wavelengths in the interval) in the normalized spectrum. We defined a contrast function as follows:

$$C(\Delta\lambda) = \frac{\text{mean}(R_{\Delta\lambda})}{\text{mean}(R)}, \qquad [3]$$

where mean(R) is the mean value of the intensities in the whole spectral range 380–780 nm, mean($R_{\Delta\lambda}$) is the mean value of the normalized intensities at wavelengths corresponding to the specific color. The wavelength bands Δλ were chosen as 620–750 nm for red, 526–606 nm for green, and 450–495 nm for blue.

3. Results and discussion

Figure 3 demonstrates reflectance spectra of samples prepared with high pigment concentration and 4 applied layers of inks. For demonstration purposes, spectra for the angle of incidence 40° and 70° under different observation angles are shown. For visualization purposes, all spectra in Figure 3 were rescaled with respect to the maximum value for all reflected directions, for each angle of incidence individually. Angles of observation were scaled with respect to the specular reflection direction (i.e. the reflectance at 40° for the incidence at 40° and 70° for the incidence at 70°). Varying balance between spectral components represents observed color change at different angles of observation. The presence of the blue spectral components in all inks is significant.

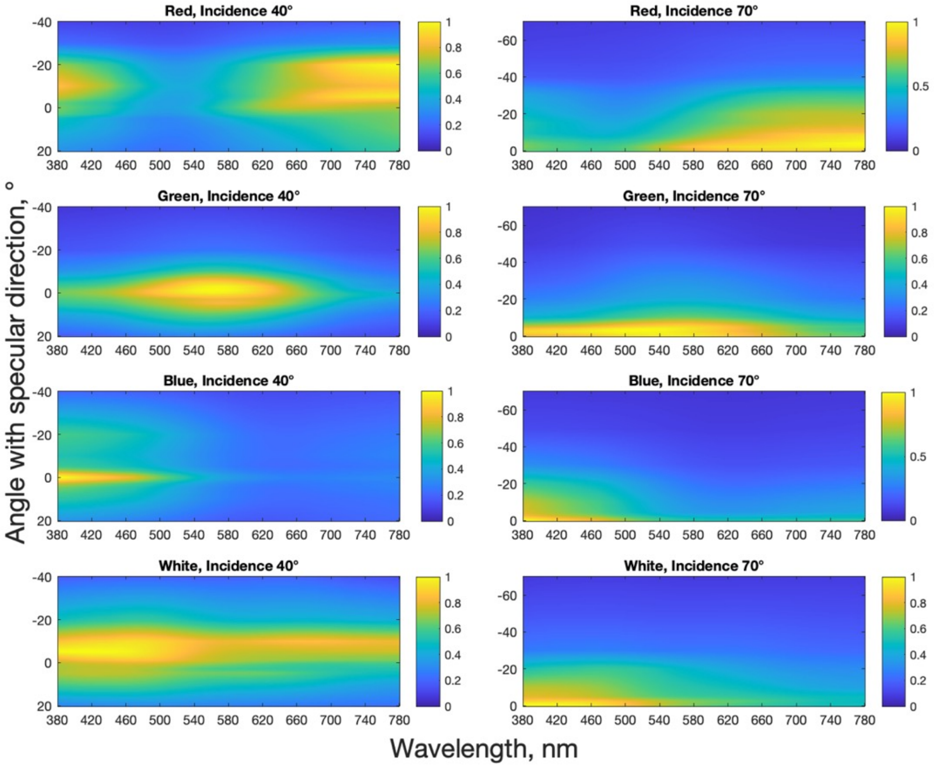

Figure 3: Scaled reflected spectra for angles of incidence (40° and 70°) for reflected angles with respect to the specular reflection direction; spectra of samples with 30% pigment concentration and 4 applied layers are demonstrated

After calculating spectral reflectance of the samples under diffuse illumination (Equation [2]), we estimated the contrast of spectral bands for the nominal colors of the pigments used (according to Equation [3]). In other words, relative contribution of the “red” wavelength band (620–750 nm) was estimated for the red ink, and for the green (526–606 nm) and blue (450–495 nm) inks, respectively. Figure 4 shows the relative color saturation with respect to different angles of observation for four types of samples: low and high concentration of pigments in the inks, as well as 1 and 4 layers of inks. These calculations were made with the spectra normalized individually for each measurement.

We simulated the result of optical mixing of two and three different ink combinations, respectively. For the two ink-mixtures, the results would correspond to the visual impression of two inks printed with 50 % area coverage, using dot-off-dot halftoning (i.e. no overlapping inks). For the three-ink mixture, the result corresponds to the visual impression of all three inks printed dot-off-dot, each with 33 % area coverage. The calculated contrasts are presented for the case of equal coverage of each pair of two colorants (Figures 4a–c), as well as an equal mixture of all three primary inks (Figure 4d). Figure 5 depicts the predicted contrast for the individual wavelength bands (corresponding to red, green, and blue) in the simulated mixtures. On the contrary to the colorants with angular constant spectral characteristics, overlap of the contrast curves for individual inks and their mixtures is angularly dependent.

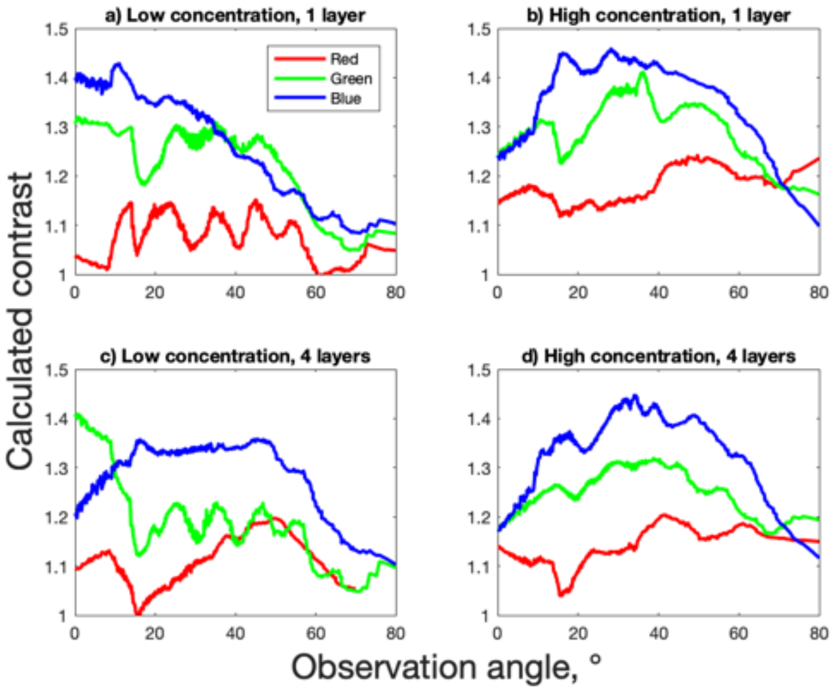

Figure 4: Calculated contrast of reflected spectra at various observation angles for red, green and blue inks after simulating diffuse illumination

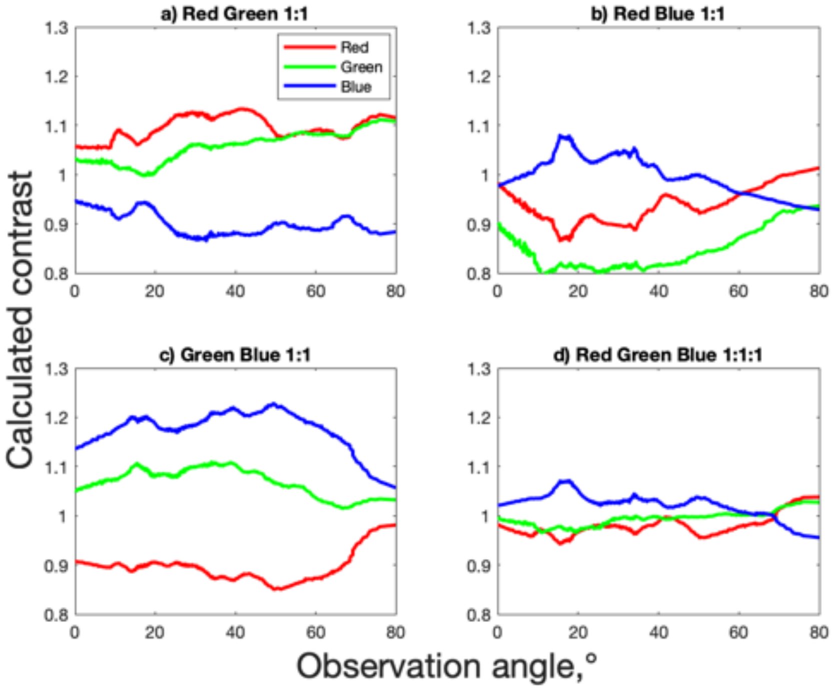

Figure 5: Calculated contrast for red, green and blue wavelength bands in the simulated mixtures of pairs of primaries and all three primary inks

The oscillations of the calculated contrast with respect to the observation angle observed at Figure 4, for the low concentration of pigments can be a result of fluctuations in measured spectra for different angles of observation and propagation of the limited measurement repeatability during the averaging over different angles of illumination (illuminated area of the rough sample surface increases with increasing angle of illumination). On the other hand, the dip in the red wavelength band (observed around 20°) is consistent with both measured spectral distribution and can be observed in the photograph in Figure 1 (blueish color for the observation angle near specular) or spectral variations with the angle of observation (Figure 3).

4. Conclusions

Obtained measured and calculated results present relative spectral bidirectional reflectance distribution of RGBW inks prepared with selectively reflecting pigments. Demonstrated angular spectral variations and calculated contrasts of individual spectral components (red, green and blue) is angularly dependent and suggest higher presence of the blue in the inks and their potential mixtures. As expected, higher concentration of pigment in the prepared inks provides better contrast of the spectral components representing nominal colors of the pigments. Future color separation strategies for halftoning algorithms may be adjusted considering calculated contrast curves in the case of dot-off-dot halftoning.

5. Future work

Future full optical characterization of selectively reflecting inks will allow modeling of the appearance in case of ink overlapping and will include ellipsometry measurements for specular reflections.

Acknowledgements

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